

# REPORT DOCUMENTATION PAGE

AFRL-SR-BL-TR-00-

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Public reporting burden for this collection of information is estimated to average 1 hour per response gathering and maintaining the data needed, and completing and reviewing the collection of information, including suggestions for reducing this burden, to Washington Headquarters Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget.

1. AGENCY USE ONLY (Leave blank)			2. REPORT DATE	3.
			14 March 1998	15 March 1995 - 14 March 1998
<b>4. TITLE AND SUBTITLE</b> Application of Approximate Inertial Manifolds and Multiresolution Techniques to Parallel Computations of Sensitivities and Design				
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<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> Beam Technologies, Inc. 687 Highland Avenue Needham, Massachusetts 02494			<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>  	
<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b> AFOSR 801 North Randolph Street, Room 732 Arlington, VA 22203-1977			<b>10. SPONSORING/MONITORING AGENCY REPORT NUMBER</b>  F49620-95-C-0027	
<b>11. SUPPLEMENTARY NOTES</b>  				
<b>12a. DISTRIBUTION AVAILABILITY STATEMENT</b> Approved for Public Release.			<b>12b. DISTRIBUTION CODE</b>  	
<b>13. ABSTRACT</b> (Maximum 200 words) The objective of this work is to develop methodologies for the efficient computation of aerodynamic sensitivities using state-of-the-art CFD techniques for use in aerodynamic shape optimization and fluids-structure interaction analysis including: analysis of multiresolution schemes to compute sensitivities, analysis of parallel implementation issues in sensitivity computations, modification of a production CFD code for parallel multiresolution computation of sensitivities, integration of sensitivities into airframe optimization.				
<b>14. SUBJECT TERMS</b>  			<b>15. NUMBER OF PAGES</b>  6	
			<b>16. PRICE CODE</b>  	
<b>17. SECURITY CLASSIFICATION OF REPORT</b>	<b>18. SECURITY CLASSIFICATION OF THIS PAGE</b>	<b>19. SECURITY CLASSIFICATION OF ABSTRACT</b>	<b>20. LIMITATION OF ABSTRACT</b>	

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APPLICATION OF APPROXIMATE INERTIAL  
MANIFOLDS AND MULTIRESOLUTION  
TECHNIQUES TO PARALLEL COMPUTATIONS OF  
SENSITIVITIES AND DESIGN  
Final Report for Contract F49620-95-C-0027

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14 March 1998

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## 1 Objectives

The objective of this work is to develop methodologies for the efficient computation of aerodynamic sensitivities using state-of-the-art CFD techniques for use in aerodynamic shape optimization and fluids-structure interaction analysis including

1. Analysis of multiresolution schemes to compute sensitivities.
2. Analysis of parallel implementation issues in sensitivity computations.
3. Modification of a production CFD code for parallel multiresolution computation of sensitivities.
4. Integration of sensitivities into airframe optimization.

## 2 Status of Effort

A commercial CFD code, RAMPANT, has been modified to calculate sensitivities of three-dimensional, compressible (including transonic) inviscid flows with respect to shape parameters using the Sensitivity Equation (SE) approach. The flow and sensitivity equations are discretized and solved on a three-dimensional unstructured mesh using a finite-volume scheme with flux-difference splitting. The discretized sensitivity system is inverted using a two-sweep point-implicit Gauss-Seidel relaxation. The algebraic multigrid method is used to accelerate convergence of this iterative solver. Significant computational savings are obtained by performing the flow and sensitivity solutions simultaneously since this avoids duplication of calculations common to both. Preliminary results have been obtained from the sensitivity solver. The next step is to apply it to computing geometric sensitivities for the transonic flow over a three-dimensional aircraft wing.

A procedure for the efficient calculation of the sensitivity of fluid-structure interaction problems has been developed. The procedure involves calculation of the flow sensitivity with respect to the geometric shape for the base configuration. The flow sensitivities are then transferred to a structural finite-element solver which solves the direct and sensitivity problems for the fluid-structure system without iterating between the flow and structural codes.

## 3 Accomplishments/New Findings

The accomplishments and new findings of the past year are listed below:

1. Implementation of the SE method in a production CFD code: RAMPANT from Fluent Inc. is a commercial CFD code for simulating compressible flows around complex three-dimensional geometries. Fluent's suite of CFD codes is the most widely-used set of commercial CFD tools. Computation of sensitivity of the flow to geometric shape parameters for inviscid flows in the subsonic, transonic and supersonic regimes has been enabled in RAMPANT. The sensitivities are calculated using the SE method in which the infinite-dimensional sensitivity system is formulated from the infinite-dimensional direct problem and then its discrete approximation is derived. The SE method offers significant advantages in terms of efficiency, accuracy and flexibility over the quasi-analytic or discrete sensitivity method (which is used in automatic differentiation technology). RAMPANT source code was made available through the establishment of a strategic

partnership between Fluent Inc. and Beam for transition of this technology to the commercial marketplace. The implementation of the SE technology in a popular CFD tool makes this technology available for solving industrial-scale problems to a large audience. This development enables design optimization, aeroelasticity and flutter calculations using state-of-the-art CFD technology and is applicable in the transonic regime. It supports the Air Force objective of affordable design through new design tools and methods.

2. Flow sensitivity calculation on three-dimensional unstructured meshes: Unstructured meshes greatly simplify the discretization of complex domains and offer the capability to adapt the mesh as the solution evolves. Implementation of the SE method on unstructured meshes significantly simplifies obtaining flow sensitivities for complex three-dimensional geometries.

3. Use of multigrid algorithm to compute sensitivities: An algebraic multigrid algorithm is used to speed up the convergence of the iterative solver employed in the sensitivity calculation. Acceleration is particularly important in cases with a large number of design variables as in airframe optimization.

4. Simultaneous calculation of flow solution and sensitivity: The sensitivity system has close similarities with the linearized flow system. Concurrent solution of the flow and sensitivity systems avoids unnecessary duplication of calculations common to both solvers and significantly reduces the computational overhead for obtaining the sensitivities.

5. Sensitivities using upwind schemes: Characteristic-based upwind schemes, such as Roe's flux-difference splitting, are used to introduce the physical properties of the flow equations into the discretized formulation by accounting for the physical propagation of perturbations along characteristics. Our implementation demonstrates the use of Roe's flux difference splitting to discretize the sensitivity equations.

6. Mathematical framework for efficient calculation of sensitivity of fluid-structure interaction: This framework provides the basis for the optimization of coupled fluid-structure systems by coupling flow and structural analysis codes without requiring iteration between the two codes. In this method, the flow solution for the base configuration and its sensitivity to geometric parameters are generated and transferred to the finite-element structural code. The structural code then solves the direct and sensitivity problems for the coupled fluid-structure system using a modified stiffness matrix. Both the flow sensitivity and the sensitivity of the coupled fluid-structure system are calculated using the SE approach. This development is an important milestone in the development of practical computational tools for the optimization of flexible structures in the nonlinear transonic and high-alpha regimes. This technology will benefit the Air Force in the aeroelastic optimization of advanced airframes and missiles.

## 4 Personnel Supported

Dr. Gal Berkooz (PI).

Dr. Rajesh Bhaskaran, Staff Scientist.

Dr. Kevin Long, Senior Scientist.

## 5 Publications

1. Bhaskaran, R. and Berkooz, G. "Optimization of fluid-structure interaction using the sensitivity equation approach" To be presented at the 4th International Symposium on Fluid-Structure Interaction, Aeroelasticity, Flow-Induced Vibrations & Noise,

2. Newjome, R.W., Berkooz, G. and Bhaskaran, R. "Analytical flow sensitivities and their use in the calculation of fluid-structure interaction" Submitted to *AIAA Journal*, 1996.

## 6 Interactions/Transitions

### 1. Presentations:

- Fluent Inc.: "A new method for fluid-structure interaction prediction" Feb. 13, 1997, Lebanon, New Hampshire. Presenter: Rajesh Bhaskaran.
- Cornell University Applied Math. Seminar: "A new method for fluid-structure interaction prediction", Nov. 6, 1996, Ithaca, New York. Presenter: Rajesh Bhaskaran.
- Aerospace Flutter and Dynamics Council: "A new method for computing CFD Accurate Aerodynamic Stiffness for Fluid Structure Interaction", Oct. 9, 1996, Williamsburg, VA. Presenter: Rajesh Bhaskaran.
- Air Force PRET members meeting: Jan. 16, 1997, Ithaca, NY. Presenter: Rajesh Bhaskaran.

### 2. Consultative and advisory functions: none.

### 3. Transitions:

- Collaboration with AFOSR PRET: Beam is a partner in an AFOSR PRET (Partnership for Research Excellence and Transition) in the area of computational partial-differential-equation (PDE) optimization for design. Beam has been working with members of the PRET to perform shape optimization on parametrized geometries created in a CAD package (Pro/E). A Navier-Stokes shape optimization code is being built using PDESolve, Beam's commercial C++ class library for numerical simulation of PDEs. The contact person is Dr. Jeffrey Borggaard, Visiting Scientist, Cornell University (Phone: (607) 255-8270, E-mail: borggajt@fred.mac.cornell.edu).
- Ongoing interaction with Lockheed Martin Tactical Aircraft Systems: Beam is collaborating with Lockheed Martin for transition of technology in the areas of sensitivity analysis and fluid-structure interaction. Applications of interest are aeroelastic tailoring optimization and flutter prediction in the transonic regime. Lockheed Ft. Worth integrated Beam's two-dimensional flow sensitivity results into ASTROS structural analysis code and tested it by performing static aeroelasticity calculations on a wing section in transonic flow. Beam will be working with Lockheed to integrate the three-dimensional sensitivities into ASTROS and to demonstrate aeroelastic tailoring optimization and flutter prediction in the transonic regime. The contact person in this interaction is Mr. Mike Love (Phone: (817) 777-2141 E-mail: love@lfcw.lockheed.com).
- Transition to Fluent, Inc.: Beam has established a strategic partnership with Fluent, Inc. who is the largest vendor of commercial CFD software. Implementation of the three-dimensional sensitivity method in RAMPANT was made

possible by Beam's partnership with Fluent. Implementation of the sensitivity technology in a popular commercial CFD tool provides a clear-cut transition path to industry. Contact person at Fluent is Dr. Dipankar Choudhury, Product Manager (Phone:603-643-2600, E-mail:dc@fluent.com).

## 7 Patent Disclosures

Berkooz, G. and Newsome, R. "A method to predict the change in shape of a solid structure as a result of force applied to it by a fluid" US Provisional Application No. 60/012,720, Feb. 1997.